Climate reconstruction in the High Arctic: development and validation of a new tree-ring-like climate proxy

Weijers, S.

2012

document version
Publisher's PDF, also known as Version of record

Chapter 1:

General Introduction

Background: arctic climate change and the need for new climate proxies

Analysis of the instrumental arctic climate record has showed it is very probable that the Arctic has warmed during the past decades and that it is very likely that precipitation has slowly increased over the 20th century (Anisimov *et al.*, 2007, McBean *et al.*, 2005). Furthermore, synthesis studies of arctic proxy climate records have shown that recent warming during the past five decades has reversed a millennia-long cooling trend, which makes it likely that this warming is the result of anthropogenic activities (Kaufman *et al.*, 2009, Miller *et al.*, 2010). Still, clear distinction between natural variability and climate change due to anthropogenic forcing in the Arctic is restricted by the scarcity of both instrumental and proxy climate data in this vast area of the globe. The instrumental arctic climate record is not only spatially limited, with weather station densities varying from only 2 per 1000 km^2 in Fennoscandinavia to 1 per 100000 km^2 in Arctic Canada, northern Alaska and parts of Siberia (McBean *et al.*, 2005), but also temporarily, with records dating back as far as the 1880s from only three areas: western Greenland, Iceland and northern Europe (Overland *et al.*, 2004). Good coverage of the arctic climate with instrumental observations only exists from the 1950s onward (Przybylak, 2000). Studies on older climate variability in the Arctic rely on proxy-based reconstructions, and out of all the proxies only lake sediments, ice cores and tree rings provide high-resolution and continuous records (McBean *et al.*, 2005). Although reconstructions of areal average Arctic temperatures based on multi-proxy analysis (including tree-ring and ice-core records) are available (Kaufman *et al.*, 2009, Overpeck *et al.*, 1997), many of the proxy records used in such studies pertain to the southern periphery of the Arctic. These records are also generally concentrated in the eastern Canadian Arctic and Greenland. Climate reconstructions based on tree-ring data even pertain, in principle, to areas outside the Arctic, when the Arctic is defined as the area where the average July temperature is below 10 ^{o}C. The northernmost tree-line roughly follows this isotherm. McBean *et al.* (2005) concluded that, as the Arctic is characterized by large natural variability and regional differences, a more homogeneous coverage of past climate is necessary for quantitative detection of change and observational gaps across the Arctic need to be filled. This emphasizes the need for new arctic climate proxies.

Svalbard: local instrumental and proxy temperature record

The instrumental temperature record of the High Arctic Archipelago Svalbard, which is the main research location of this thesis, is relatively long. Systematic measurements on Svalbard first started in Green Harbour in December 1911. This makes the archipelago well-suited for climate proxy studies as the available instrumental record allows for extensive calibration and verification of proxy data against observational data. The homogenised Svalbard Airport temperature record exists of measurements from several weather stations, mainly located

in the Isfjord-area in Spitsbergen. These measurements were all transferred to match temperatures measured at the current Svalbard Airport weather station (Kohler *et al.*, 2002, Nordli & Kohler, 2003). Although relatively long, the instrumental record is still too short for in-depth analysis of long-term climate variability.

The available climate proxy record of Svalbard, besides more coarse paleoclimatic estimates based e.g. on pollen assemblages (Rozema *et al.*, 2006), comes mainly from ice-core data (Divine *et al.*, 2011, Isaksson *et al.*, 2005a, Isaksson *et al.*, 2005b). Stable oxygen isotope measurements from ice-cores are commonly used and are a valuable source for past temperature changes. However, the oxygen isotope records from Svalbard correlate better with the instrumental record from northern Norway than with the local record. Thus, these records do not necessarily best represent local high arctic climate variability. Also, although they generally have an annual resolution, year-to-year correlations with instrumental average winter (December-February) temperatures are low (Divine *et al.*, 2011). Lower frequency temperature variability, on the other hand, is well captured by these records, which makes them valuable temperature proxies. The winter (December through February) temperature signal contained in the ice-cores is markedly stronger than the annual mean temperature signal (Divine *et al.*, 2011). High-resolution arctic biological temperature proxies, which generally represent climatic conditions during the growing season (Miller *et al.*, 2010), would therefore be a welcome addition to the proxy record.

Arctic trees: dwarf shrubs

Tree-ring records are a great source for paleoclimatic information, as they are generally (relatively) easily replicated, have a high-resolution, and are continuous and precisely dated. Dendroclimatology is the scientific subfield in which climate is reconstructed using the link between tree-ring width timeseries and the instrumental climate record (Fritts, 1976). Besides tree-ring width, other annual plant (growth) characteristics, like maximum late-wood density (e.g. Briffa *et al.*, 1992), height increments (e.g. Pensa *et al.*, 2005) and carbon isotope ratios (e.g. Gagen *et al.*, 2007) can be, and have been, successfully used for climate reconstruction. Trees are however obviously absent in the Arctic above the tree line and, consequently, dendroclimatological possibilities in this region have hardly been investigated, at least until recent years. Annual growth rings are however by no means restricted to trees, but are also commonly present in herbs, shrubs, and dwarf shrubs (Schweingruber & Poschlod, 2005). Relatively recently, an increasing amount of studies have shown the dendrochronological potential of several (dwarf) shrub species in regions previously unexplored by dendrochronology, such as deserts (e.g. Chartier *et al.*, 2009), high mountains (e.g. Bär *et al.*, 2006), and the Arctic (e.g. Woodcock & Bradley, 1994). The utilization of annual rings of small plants is furthermore listed among the promising new topics in dendrochronology (Eckstein & Schweingruber, 2009). In the Arctic annual growth ring chronologies of several shrub species (mainly *Salix*) have been developed thus far, which were successfully linked to climatic parameters (Blok *et al.*, 2011, Forbes *et al.*, 2010, Schmidt *et al.*, 2006, Zalatan & Gajewski, 2006). These chronologies are all shorter than a hundred years and sometimes

only barely surpass the local instrumental records. Still, as most arctic instrumental records only started in the 1950s, such chronologies might be relevant for climate reconstruction. Furthermore, growth chronologies of these species might prove invaluable for answering climate-related ecological questions.

Cassiope tetragona

Annually resolved growth chronologies exceeding a hundred years have been reported for the ericaceous, evergreen dwarf shrub *Cassiope tetragona*, commonly named Arctic (white) bell heather. The species is strongly branched and has an initial upright, but later prostrate, growth habit (Figure 1.1).

Figure 1.1 *Picture of Cassiope tetragona mats in Endalen, Svalbard, showing its initial upright and later prostrate growth habit.*

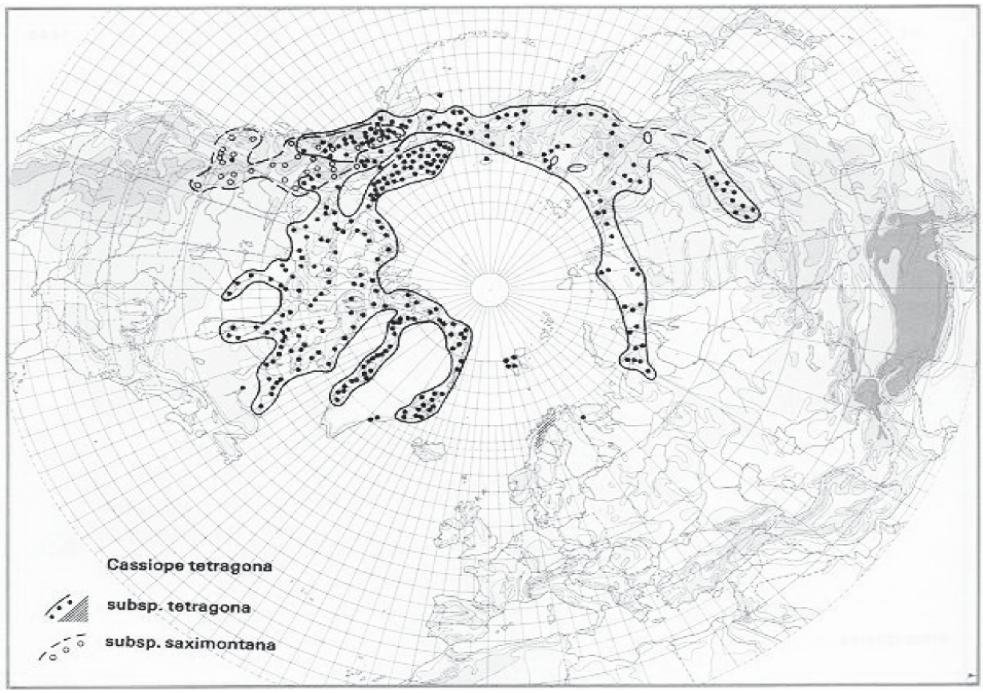

Figure 1.2 *Distribution map of Cassiope tetragona (after: http://linnaeus.nrm.se/flora/).*

The species has a circumarctic distribution (Figure 1.2). While it is a dominant species in many ecosystems in the High Arctic, it is less common in the Low- and Subarctic, where it is only abundant on calcareous soils at higher altitudes (Havström *et al.*, 1993). In Svalbard, *C. tetragona* is a widespread and common species in dry localities, especially on slopes with some snow cover in winter (Rønning, 1996). Growth chronologies for this species have been used for the reconstruction of summer temperatures back to 1895 in the Canadian High Arctic (Rayback & Henry, 2006). In an earlier study, the discovery of well-preserved subfossil *C. tetragona* plant material resulted in Little Ice Age temperature estimates in the same area (Havström *et al.*, 1995). Neither of these studies used ring width as measure of annual growth. Although secondary radial growth is present, and distinct rings are visible in cross-sections of its stems (Rayback *et al.*, 2011), ring width studies have been unsuccessful so far (F. H. Schweingruber, pers. comm. 2008). Instead other annual growth parameters, such as stem length, number of leaves, flower buds, and peduncles were used. These parameters are measureable, as this species forms smaller leaves at the beginning and end of each growing season, which results in wave-like leaf patterns visible along the stems. This feature was first recognized and described by Warming (1908). The species is called *tetragona* as it leaves grow in opposite sets, which alternate in angles of ninety degrees, thereby forming four rows of leaves. Leaves can remain attached to the stems for relatively long periods, of time (up to 40 years) and annual growth can be measured over longer periods as leaf scars remain visible thereafter. Leaf scars distances decrease at the end of the growing season, leading to patterns

similar to those of leaf lengths, allowing for the detection of annual growth (Johnstone & Henry, 1997). The development of stem length growth chronologies based on this method is, however, limited by the fact that leaf scars become increasingly hard to distinguish over time and the outer bark layer of *C. tetragona*, which includes the leaf scars, loosens and finally drops off after several decades. Recently a new method for the measurement of annual shoot length growth was reported, which allows for measurement of annual *C. tetragona* stem length growth further back in time than previously possible, based on the presence of so-called wintermarksepta (WMS) in its stems (Rozema *et al.*, 2009). WMS are visible in longitudinal sections as dark bands within the pith of the stems, which are located at the same place as the lows in leaf scar distances. Distances between WMS match the annually summed distances between leaf scars and are therefore an alternative measure for annual stem length growth. Through this technique, annual stem length growth of *C. tetragona* can be measured over the whole length of each stem.

Growth limiting factors

The reliability of climate reconstructions based on growth chronologies relies on the strength and stability of the relationships between chronologies and instrumental records. The strength of the relationship between plant growth and a specific environmental parameter is generally determined by the extent that growth is limited by this environmental factor. A wide range of factors, which may all be interrelated, can constrain plant growth. Among the most important factors are water availability, temperature, nutrient availability and light. The fact that maximum growth rate is generally determined by the most limiting factor, is an important principle in dendrochronology (Fritts, 1976). For dendroclimatology it is important that the most limiting factor remains the same over long periods of time. If, for example, temperature increases to a point where it becomes no longer, or to a lesser extent, a limiting factor for growth, another factor can become the most limiting. Then, the link between growth and temperature will become less strong or cease to exist. This can result in a non-linear relationship. Many northern tree-line species show such a decrease in sensitivity to the rising temperatures of the second part of the 20th century. This phenomena has become known as the 'Divergence Problem' (D'Arrigo *et al.*, 2008), which forms a major challenge for dendroclimatology. Growth chronologies from species with a divergent response to temperature may fail to reproduce past warming events to their real extent. An increased sensitivity to drought as a result of rising temperatures has been proposed as a possibly underlying cause of divergence. Wilmking and Juday (2005), for example, found a decrease in growth response of white spruce (Picea glauca) to recent warming along a longitudinal precipitation gradient in Alaska: trees from relatively wet areas responded positively to warming, while trees from dryer localities showed a decline in growth rate. Assessment of the stability of climate-growth relationships in (field) experiments and along climatic gradients is therefore essential to verify the reliability of annual growth parameters as climate proxies.
In the Arctic, growing season temperature is likely to be among the main factors limiting shrub growth, as has been shown for *Betula nana* in northeast Siberia (Blok *et al.*, 2011) and

Salix lanata in the northwestern Russian Arctic (Forbes *et al.*, 2010). In other studies other factors have, however, been pinpointed as the strongest driver of arctic shrub growth. A *Salix alaxensis* ring width chronology from Arctic Canada, for example, correlated strongly with December through March precipitation (Zalatan & Gajewski, 2006) and radial growth of *Salix arctica* from northeast Greenland displayed a strong negative correlation with June snow cover, but was not correlated to summer temperatures (Schmidt *et al.*, 2006). For *C. tetragona* there is both experimental and correlative evidence that its growth is mainly temperature-limited. Strong positive correlations between several *C. tetragona* annual growth parameters and mean July/summer temperature in the European High and Sub Arctic and in the Canadian High Arctic have been reported (Aanes *et al.*, 2002, Callaghan *et al.*, 1989, Havström *et al.*, 1995, Johnstone & Henry, 1997, Rayback & Henry, 2005, Rayback & Henry, 2006). In contrast, Callaghan *et al.* (1989) identified precipitation as the most important driver of growth on Svalbard. Their conclusion was based on multiple regression analyses between *C. tetragona* leaf performance variables and monthly climate data. Still, July temperature correlated strongly with the leaf variables as well. Rozema *et al.* (2009) found a strong correlation between annual stem length growth and average summer temperatures, next to a strong positive response of *C. tetragona* growth to experimentally increased temperatures with Open Top Chambers (OTCs) in a field experiment on Svalbard. Another field experiment with greenhouses has similarly shown the sensitivity of *C. tetragona* growth to growing season temperatures on Svalbard (Havström *et al.*, 1993). In contrast, growth did not respond to artificially increased temperatures and seemed to be more nutrient-limited in subarctic Sweden (Havström *et al.*, 1993). A lack of response to OTC-warming was also reported in the Canadian High Arctic (Rayback & Henry, 2005). Still, annual growth of *C. tetragona* seems, in general, to be primarily limited by temperature, especially in the High Arctic. Growth chronologies constructed from populations in this area could therefore likely serve as temperature proxy. Furthermore, as *C. tetragona* is not grazed upon by e.g. reindeer (Havström *et al.*, 1993) or other herbivores (Mallik *et al.*, 2011), potential climate signals in growth chronologies of this species are undisturbed by grazing. In the subarctic growth could perhaps be more limited by other factors than temperature, such as nutrient availability, indicating that increasing temperatures might result in a decrease in growth response of *C. tetragona* there. If so, a Divergence Problem might thus be present in this species. Furthermore, all the evidence for a positive growth response to artificial warming comes from short-term field experiments. As the short-term response of plant species to experimental warming might differ from the long-term response (Hollister *et al.*, 2005), longer-term experiments are needed to confirm the sensitivity of *C. tetragona* growth to temperature.

Age-related autocorrelation

Ring-width and other plant growth time-series are, besides consisting of randomly varying components, generally also characterized by a type of non-randomness called autocorrelation (Cook & Kairiukstis, 1990, Fritts, 1976). Ring widths of the current year can, for example, be

influenced by the width of the previous year ring. Such trends can have an age-related cause through uneven growth over a plants' lifetime, but can also be a reflection of low-frequency climate changes. Juvenile growth trends have been described for *C. tetragona* branches: stem length growth is smaller in the first years of a (side-) branch's lifetime (Rayback & Henry, 2005). In dendroclimatology, non-climatic autocorrelation has to be removed from growth chronologies to prevent detection of spurious climate-growth relationships. Non-climatic growth trends are eliminated by dividing the time-series by an estimation of these trends (Cook *et al.*, 1990, Cook, 1985). This process is called detrending. The accidental removal of low-frequency climatic trends with non-climatic growth trends by detrending can, however, sometimes lead to a false detection of the Divergence Problem (Esper & Frank, 2009). Trend elimination for the relatively short (dwarf) shrub growth series has thus far not as well been studied as for the generally longer tree-ring series.

Carbon isotope discrimination

Annual growth parameters of *C. tetragona* can thus potentially be used as an arctic temperature proxy. Climate change is, however, not synonymous with temperature change, but can be manifested as changes in other climatic parameters. Precipitation, e.g., has increased in many regions of the world between 1900 and 2005, while the global area affected by drought has likely increased since the 1970s (IPCC, 2007). On Svalbard an average increase of 2.8% per decade in annual precipitation was observed between 1912 and 2000 (Hanssen-Bauer, 2002). General assessment of precipitation change in the Arctic is however restricted by the limited amount of observations available (McBean *et al.*, 2005, Weller *et al.*, 2005) and existing problems with the accurate measurement of snowfall and rainfall in cold environments (Goodison *et al.*, 1998). Also, reconstructions of past precipitation changes are less common than temperature reconstructions (Miller *et al.*, 2010). Carbon isotope ratios in annual plant fragments can however potentially capture strong precipitation signals (e.g. Fichtler *et al.*, 2010). This is a direct result of the fact that the reaction of the lighter $^{12}CO_2$ with the enzyme Rubisco during photosynthesis is faster than with $^{13}CO_2$, which causes plants to be more depleted in ^{13}C than source air (Farquhar *et al.*, 1989, Farquhar *et al.*, 1982). This discrimination against the heavier isotope by Rubisco is largely prevented when plants close their stomata to limit water loss. Dry periods will thus generally result in plant tissue less depleted in ^{13}C, than plant tissue formed in wetter periods. Consequently, a climatic footprint is left behind. This is however only the case when plants use the C3-photosynthetic pathway. In C4-plants CO_2 is initially bound by another enzyme, phosphoenolpyruvate (PEP), leaving discrimination against ^{13}C during photosynthesis insensitive towards stomatal conductivity (Evans *et al.*, 1986, Farquhar *et al.*, 1989). Different components of wood have different stable carbon isotope ratios, with e.g. lignin being more depleted in ^{13}C than cellulose. Climate proxy studies based on carbon isotope discrimination have therefore mainly been concentrated on analysis of $^{13}C/^{12}C$ ratios in cellulose of annual increments, as cellulose is the most abundant component of wood. However, cellulose extraction is a time-consuming process and whole wood $^{13}C/^{12}C$ ratios may contain the strongest climate signal (Loader *et al.*, 2003).

Climate signals in δ^{13}C-chronologies of annual shoot length increments of *C. tetragona* have previously been reported. In Svalbard, δ^{13}C-values of cellulose in shoots correlated negatively with combined April and May precipitation sums (Welker *et al.*, 1995). These results can probably be best explained by large amounts of spring snowfall leading to increased water availability during summer and thus increased discrimination against ^{13}C (more negative δ^{13}C-values). In a second study, carbon and oxygen isotope ratios of *C. tetragona* annual shoot length fragments from the Canadian Arctic were linked to indexed annual modes of the dominant atmospheric circulation patterns in the Arctic, the Arctic and North Atlantic Oscillation (Welker *et al.*, 2005). These annual climate signals found in the isotopic characteristics of annual shoot length fragments are to some extent remarkable, as annual shoot lengths are not just the product of one year's growth. Radial growth is present in *C. tetragona*, as distinct rings are visible in radial cross-sections of *C. tetragona* stems (Schweingruber & Landolt, 2005). Therefore, it is likely that most annual shoot length fragments contain plant material that was formed over multiple years. The fact that climate signals have been identified in the isotopic signature in such annual fragments, however, suggests that these fragments are dominated by the year in which they were initially formed and that isotopes in *C. tetragona* might indeed record past climate variability. Still, the climate signal might partly be obscured by radial growth, and more research is needed into the relationship between climatic parameters and isotope records of *C. tetragona*. Moreover, experimental evidence for the reported link between water availability and carbon isotope discrimination in this species is lacking. The scientific basis for the use of carbon isotopes of *C. tetragona* as climate proxy is therefore, up to now, narrow.

General aims en thesis outline

The general aims of this thesis were the development, validation, and use of annual growth parameters and carbon isotope discrimination of *C. tetragona* as an arctic climate proxy. For this, climate-growth relationships were tested by examining correlations between instrumental climate data and growth chronologies, both locally and over a climatic gradient. Furthermore, climate-growth relationships were validated through the manipulation of climatic parameters in field experiments. During seven years ambient summer air temperatures were enhanced through the instalment of Open Top Chambers (OTCs) over the tundra vegetation during summer months at a high arctic site. At another site, ambient precipitation was doubled by manually adding water to the vegetation during four growing season. In addition, Photosynthetically Active Radiation (PAR) was experimentally reduced during two growing seasons, simulating projected increased cloudiness resulting from climate change, by the instalment of cubic tents, consisting of gauze, over the vegetation. The effect of these manipulations was tested by comparing growth of *C. tetragona* in control plots with that in manipulated plots. The effects of precipitation and temperature on stomatal conductance, and thereby on carbon isotope discrimination (Δ), were tested by comparing discrimination values in annual leaf cohorts and stem fragments from control and doubled ambient precipitation plots and δ^{13}C in leaves from different light regimes.

Chapter 1: General Introduction to this thesis.

Chapter 2: describes the construction of a *C. tetragona* stem length growth chronology for a high arctic site in Svalbard. This chronology is, with 169 years, the longest chronology developed thus far. Climate-growth relationships are examined through the calculation of Pearson correlation coefficients between the monthly mean temperature and precipitation data from the local instrumental climate record on the one hand, and the growth chronology on the other. To test whether the standardization technique used to remove growth-related autocorrelation from the stem length series, multiple regression growth-climate models were developed for both the nonstandardized and standardized chronology. Finally, linear growth-climate transfer functions were calibrated and verified over equal, but separate parts of the instrumental record and local mean July temperatures were reconstructed back to 1876.

Chapter 3: To test whether climate reconstruction based on growth parameters of *C. tetragona* is hampered by divergence, the climate-growth association in *C. tetragona* is tested along three different sites over a high to subarctic climatic gradient: close to its cold tolerance boundary at Ny-Ålesund, Svalbard (78°55'N, 11°56'E), at its assumed climate optimum at Endalen, Svalbard (78°11'N, 15°44'E) and near its European southern limit at Abisko, Sweden (68°21'N, 18°49'E). Four annually resolved growth chronologies (stem length, total leaf length, number of leaves and average leaf length) were constructed for each site. All chronologies at the sites are new, except for the stem growth chronology at Endalen, which was developed for Chapter 2. We test whether the climate-growth relationship in *C. tetragona* is fully linear over this broad temperature range. Furthermore, we analyze the response of *C. tetragona* to seven years (2004-2010) of artificial warming by Open Top Chambers at a high arctic site near Ny-Ålesund.

Chapter 4: Mean monthly temperatures are a coarse unit in marginal regions, such as the Arctic, where the growing season is very short. A finer differentiation with respect to variation in warmth between growing seasons might help to improve climate-growth models and thereby climate reconstructions. As an alternative to monthly averages, growing degree-days (GDD) could perhaps better explain observed annual growth. GDD is an overall measure for the intensity of the growing season and is calculated as the cumulative temperature above a given threshold. At high latitudes, this threshold is usually set at 5 °C. Here, it is tested whether GDD sums are indeed a better predictor of *C. tetragona* stem length growth than mean monthly temperatures over the same gradient as in Chapter 3. For this the daily mean temperature data were used from weather stations nearby the sampling locations to calculate growing season intensity as GDD_5. Furthermore, the previously developed dataset of annually resolved *C. tetragona* stem length growth chronologies from each of the three sites was used. Finally GDD_5 at Svalbard was reconstructed beyond its instrumental record, which started in 1912, using the long stem length chronologies from Ny-Ålesund and Endalen (of 154 and 169 years respectively), the first of which was not yet utilized for reconstruction purposes.

Chapter 5: In this chapter the use of annual growth parameters of *C. tetragona* as an arctic temperature proxy is further validated and the potential of carbon discrimination values in annual *C. tetragona* fragments as a climate proxy is tested. In separate field-experiments precipitation was doubled and Photosynthetically Active Radiation (PAR) was halved and the effects of summer precipitation and shading on annual growth parameters of *C. tetragona* were consequently assessed. Furthermore it was tested whether carbon isotope discrimination in *C. tetragona* was affected by the enhanced precipitation regime and whether the carbon isotope signature differed between leaves from different light regimes. Finally an annually resolved Δ-stem chronology (1975-2008) was developed and relationships with the local climate were examined.

Chapter 6: General Discussion.

As Chapters 2-5 were written for publication in peer-reviewed journals as well as for this thesis, some overlap in content was inevitable, especially in the Introduction and Material & Methods sections.